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Variability in regional scale estimates of carbon stocks in boreal forest ecosystems: results from West-Central Alberta

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Abstract

Aboveground biomass, forest floor, and soil carbon (C) stocks were estimated for a transitional boreal region in western Alberta using available forest inventory data, model simulation, field observed plot data, and soil polygon (area averaged) information from the Canadian soil organic carbon database (CSOCD). For the three C pools investigated, model simulation provided a regional estimate, while forest inventory, plot, and soil polygon data provided an estimate of the spatial variation. These data were used to examine the variation of the C estimates, in both temporal (e.g. climate change) and spatial (e.g. soil physical characteristics) dimensions. Using the carbon budget model of the Canadian forest sector (CBM-CFS2) the regional average aboveground biomass C was estimated at 43 Mg C ha^{-2}, similar to the estimate from the 1994 Canadian forest inventory (50 Mg C ha^{-2}). Model simulation over the period 1920–1995 elucidated the major role that disturbances (harvest, fire and insects) play in determining the C budget of the region. Decreases in stand replacing disturbances over the period resulted in an accumulation in biomass C.

Regional estimates of forest floor C using aggregated plot data, CSOCD (forested area only) data, and CBM-CFS2 simulations were in close agreement, yielding values of 2.9, 3.4 and 3.3 kg C m^{-2}, respectively. Regional estimates of total soil C using the three methods were more divergent (14.8, 8.3, and 15.6 kg C m^{-2}, respectively).

An exponential relationship between clay content and biomass for mature coniferous stand types was found ($r^2 = 0.68$), which is reasonable considering that as a site variable, texture affects tree growth through the modification of nutrient and water availability. The relationship was used to predict the range of potential values for biomass C at maturity across the region. Forest inventories of biomass seldom provide enough data across the range of ages and stand types to develop stand growth curves that capture the variation in growth across the landscape. Consequently, growth dynamics must be inferred from a large area to provide enough biomass-to-age data, which results in a loss in the ability to use it to predict C pools and fluxes at a small scale. Using relationships between site factors (such as soil texture) and biomass C provides a means to modify inventory-based biomass-to-age relationships to assess the variation across the region as well as make predictions at a higher spatial resolution. This is relevant where both spatial extent and a finer scale are required, but site-specific biomass-to-age relationships are unavailable.

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1. Introduction

Biomass, forest floor, and mineral soils in Canadian boreal forests contain approximately 200 Pg of carbon

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approximately 15% of the total carbon (C) stored in the terrestrial biosphere (Apps et al., 1993; Smith and Shugart, 1993). The dynamics of these C pools are highly connected. The organic C content of the biomass, forest floor, and the mineral soil is the result of interactions between climate, succession, vegetation type, soil moisture, temperature, nutrient availability, soil texture, and disturbance regime. These interactions control the primary processes of production and decomposition, and in turn regulate net ecosystem C dynamics (Peng et al., 1998).

Boreal forest biomass is known to vary with disturbance regime (Larsen and MacDonald, 1998), successional status (Apps and Price, 1996), soil type and soil nutrients (Kimmins, 1996), climate (Shugart et al., 1992), topographic position (Hairston and Grigal, 1991; Schmidt and Carmean, 1988), and human impacts (Brown et al., 1999; Laurance et al., 1997). However, the degree to which the biomass varies across mesoscale (1 to 100 km^2) landscapes, and how this variation relates to site variables is difficult to estimate. Stand biomass C accumulation is affected by site factors, and by disturbance patterns both directly through C release to the atmosphere and C transfer to dead organic matter (DOM) pools and indirectly, through modifications to site factors resulting from the disturbance.

The effect of disturbance feedback on site factors influencing the accumulation, transfer and release of C is particularly important in boreal systems (Kimmins, 1996). Models of C dynamics, even those that contain a representation and linkage between above and belowground dynamics, often treat the site as if in steady state. In these models, the direct emission of C is accounted, but potential changes to the site caused by disturbances (e.g. removal of duff layer, remaining slash, nitrogen (N) loss) and the effect on subsequent stand growth is not considered. Including a dynamic relationship between biomass accumulation and site variables introduces a feedback mechanism to explain the variability in forest biomass C estimations.

Average C estimates, appropriate for larger scale ecoclimatic provinces and national scale modelling, are inadequate for capturing this variability at a local scale. The bedrock and soil cover in central Canada's boreal forest zone is still responding to a series of glaciations (Harden et al., 1992) and is characterized by thin till soils, interspersed with groundwater-conducting eskers and areas of washed-out clay material. As well, there are large pools of C in lakes that are effectively permanently removed from the C cycle dynamics of forest biomass and soil pools (Campbell et al., 2000). Heterogeneity in the landscape results in sites differing in micro climatic conditions, physical and chemical properties. Estimation of C pools and fluxes at a higher spatial resolution requires a knowledge of the factors which cause this variability in the landscape and how they are related to stand growth and C turnover rates. Most of the regional, national and global models estimating the C dynamics are driven by vegetation dynamics and are commonly based on the concept of some average site conditions. Such parameterization is difficult to substantiate when the landscape is highly heterogeneous.

The objective of this study was to assess the variability in C estimates, and determine the extent to which this variability can be explained in terms of local site variables. The precision of C estimates could then be improved through the development of local adjustment terms to the regional relationships (derived from the inventory) using response functions based on local site factors (Uddin et al., 2001). Estimates of biomass, forest floor and total soil C pools were compared, and the associated variability examined at the regional and local scales. To explain the variability on a local scale, empirical relationships between nitrogen, texture and biomass C were examined. For C budget modelling at a higher spatial resolution, the potential to incorporate the influence of site variables to capture the variation in biomass C dynamics at a finer scale was assessed.

2. Methods

2.1. Study area

The study region consists of the Cordilleran ecoclimatic province (Ecoregions Working Group, 1989) in Alberta (Fig. 1). This area (over 12 Mha total, approximately 9 Mha forest land) contains four ecoclimatic regions but is dominated by the boreal southern Cordilleran ecoclimatic region (SCb). This area represents a transition zone between boreal and Cordilleran vegetation on the lower slopes of the Rocky Mountains. Lodgepole pine (*Pinus contorta*) is the predominant

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Fig. 1. Location of study area, Cordilleran ecoclimatic province in Alberta, Canada.

tree species and is frequently found in pure or mixed stands with similarly aged trembling aspen (*Populus tremuloides*) or white spruce (*Picea glauca*). Other species include balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*). Total precipitation in this region ranges from 400 to 600 mm annually, with growing season average temperature around 10 °C. The dominant soil types (those represented by well drained deep loamy soils) are the Gray Luvisols and Brunisols (Soil Classification Working Group, 1998) with pockets of peatlands in lowland areas.

2.2. Source data

Aboveground biomass was estimated using available forest inventory data (Gray and Power, 1997), CBM-CFS2 modelling (Kurz and Apps, 1999) and field observed stand data (LaRoi and Pluth, 1986). Forest floor, and soil C stocks were estimated using CBM-CFS2 (Kurz and Apps, 1999), field observed stand data (LaRoi and Pluth, 1986), Soil profile and organic C database for Canadian forest and tundra mineral soils (Siltanen et al., 1997), and soil polygon information from the Canadian soil organic carbon database (CSOCD) compiled by Tarnocai and Lacelle (1996). Model simulation provided regional estimates, while forest inventory, field observed, and soil polygon data were used as indicators of the spatial variation. For comparison of biomass C, the aboveground biomass excluding submerchantable (trees less than merchantable size) biomass was used since the site–biomass relationships examined did not include submerchantable biomass.

2.3. Forest inventory data

Inventory-based biomass estimates were derived from the 1994 Canadian forest inventory (Gray and Power, 1997) for inventoried forest land (CanFI94). The inventory is a compilation of provincial resource inventories and accounts for merchantable stemwood volume. Inventory data in this region consists of separate smaller inventories collected over a period from 1951 to 1991, however, most of the area is inventoried within 10 years of the average (1978). Volume to biomass conversion and biomass estimates for other aboveground components were obtained using the method and conversion factors described in Penner et al. (1997). Biomass C was then derived from biomass by multiplying by a factor of 0.5.

2.4. Field observed data

Field observed data from LaRoi and Pluth (1986) provided information on tree biomass, site and soils including: site characteristics, soil drainage class, forest floor thickness, bulk density, total N and C content, mineral soil horizon thickness, % clay and silt content. A total of 39 plots from mature stands were used in the present study, within a localized area of the SCb region, between 54° and 54° 30′N latitude, and 115° 20′ and 118° 30′W longitude. Regression analyses were used to determine the relationship between aboveground biomass, clay content and total N. The best regression equation was chosen based on the adjusted r^2.

Field observed soil C was also obtained from the soil profile and organic carbon database for Canadian forest and tundra mineral soils (Siltanen et al., 1997).

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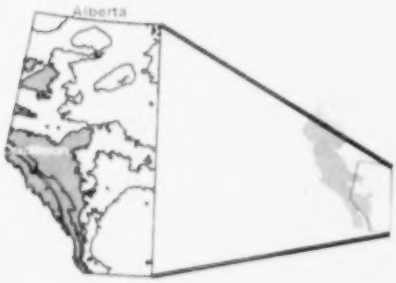

Fig. 1. Location of study area: Cordilleran ecoclimatic province in Alberta, Canada.

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Field observed soil C was also obtained from the soil profile and organic carbon database for Canadian forest and tundra mineral soils (Siltanen et al., 1997).

A total of 146 forested sites from this dataset, distributed throughout the study area, were used to estimate the range of forest floor and soil C content. The estimates were combined for each of the four ecoclimatic regions present in the area, and a total area weighted average calculated. This database contains information on soil drainage class, forest floor thickness, bulk density, total N and C content, horizon depth, and % clay and silt content. Stand biomass (at maturity) was predicted for the plots from Siltanen et al. (1997) using the site–productivity relationship derived from the LaRoi and Pluth (1986) dataset. Soil polygon data was obtained from the Canadian soil organic C database (CSOCD). Soil C information with data attributes were combined for Alberta from existing large scale, soil survey maps and their reports. A detailed description of the database, including the structure and attributes, is given in Tarnocai and Lacelle (1996). The soil C content was initially determined on the basis of soil type polygons. Each polygon was allocated as a percentage of the grid cells forming the database. Surface soil C was calculated for the first 30 cm while total soil C content was calculated to the depth of soil.

2.5. Modelling

Simulated results for biomass and soil C pools were obtained using the carbon budget model of the Canadian forest sector (CBM-CFS2). CBM-CFS2 is a spatially distributed simulation model which accounts for C pools and fluxes in forest ecosystems whose dynamics are primarily driven by stand replacing disturbances (Apps and Kurz, 1993; Kurz and Apps, 1999; Kurz et al., 1992). The CBM-CFS2 model uses

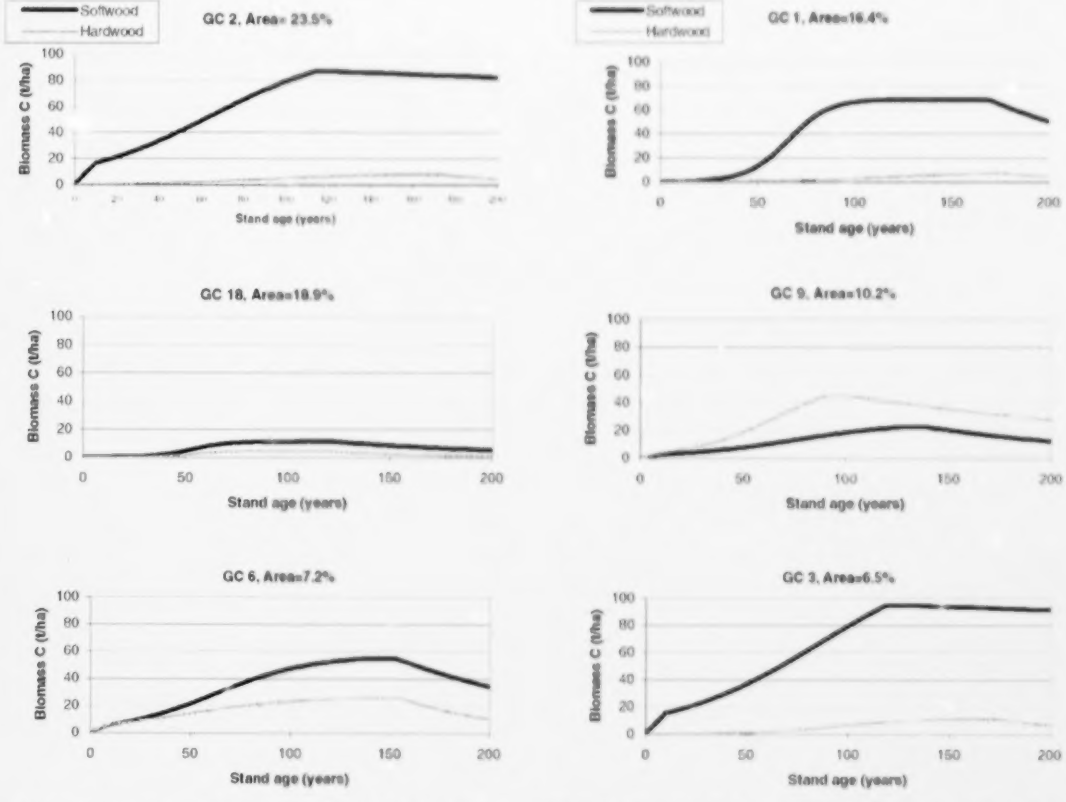

Fig. 2. Sample growth curves used in CBM-CFS2 for the Cordilleran ecoclimatic province in Alberta. The growth curves are fitted to data from the Bonnor, 1985 biomass inventory which was based upon the 1981 Canadian forest volume inventory.

biomass growth curves, derived from the Bonnor (1985) forest biomass inventory (which was derived from the 1981 Canadian volume inventory) to describe the accumulation of biomass C as a function of stand age. The model was also calibrated (determining the initial conditions in 1920) using the age-class structure of the Bonnor (1985) biomass inventory. C stocks and fluxes are estimated through simulated growth changes and through the application of disturbances based on the historical disturbance record for the region. In the model, the simulation area is divided into spatial units having broadly similar vegetation characteristics. Within each of these spatial units, the model simulates the dynamics of groups of stands (state variable objects (SVOs)) having similar inventory indices for species, productivity, stocking, and age class characteristics. A unique growth curve pair (for hardwoods and softwoods) is associated with each such grouping. Although not spatially explicit within a spatial unit, the model estimates of C dynamics are based on the dynamics of the distinct stands (SVOs) within the spatial unit as recorded in the inventory by these classification indices. For this region, there are 18 growth curve pairs, composed of a biomass growth curve for hardwood and softwood general species types. Biomass growth for more than 80% of the area (Fig. 2) is represented by 6 of the 18 growth curve papers. The forests for the overall area are predominantly softwood; hardwood normally being present in conjunction with the dominating softwoods; growth in the largest mixedwood type has a higher hardwood biomass component than softwood, however hardwood represents a relatively small fraction for most of the area.

Although the model estimate for a region accounts for growth and mortality, it does not account for changes in growth rates with changes in the environment over time. The inventory biomass for a stand inherently includes the integrated effect of the growing conditions that existed throughout the stand's life. Consequently, stands of differing age and location, although they may be of the same classified 'type', may not have had the same growing conditions. By using the inventory data as a chronosequence to calibrate the growth curves, the model thus does not distinguish these changes in growing conditions and instead estimates a temporal average of these changes (weighted by the age class distribution). On average the inventory chronosequence-derived growth curve is representative over the region from which the inventory data is used, but for application at a regional level, an assessment of the variation in growth, and the relation to site factors (not contained in the inventory classifiers) may be required.

3. Results and discussion

3.1. Estimating the biomass carbon pool

Aboveground biomass C estimates from the Canadian forest inventory (1994), and from simulation (CBM-CFS2) were compared and found to be in close agreement. The inventory average biomass C was 50 Mg C ha^{-1}, and the CBM-CFS2 estimate was 43 Mg C ha^{-1} (model estimates range from 26 Mg C ha^{-1} in 1920, increasing to just over 43 Mg C ha^{-1} in 1995). For the total biomass C (aboveground biomass, excluding submerchantable biomass), the inventory and CBM-CFS2 estimates were 426 Tg (area of 8.54 Mha) and 404 Tg (area of 9.36 Mha), respectively. The difference in area is a result of the two estimates being based on different inventories. The CBM-CFS2 was calibrated using the 1981 volume inventory while the inventory estimate is based on the 1994 volume inventory. The biomass estimates were broken down by hardwood and softwood species group (Table 1). As a species group, softwood constituted 75% of the total biomass for the inventory estimate and 80% of the total for the model estimate. Differences in the estimates also resulted because, unlike the CBM-CFS2, the inventory estimate does not account for biomass growth or depletion due to natural mortality and disturbances for stands inventoried earlier or later than the average year. Therefore, single point-in-time estimates of biomass from the inventory for a large region will contain some degree of inaccuracy. Fig. 3 shows the distribution over time of the area in the inventory. By comparison, the influence of the difference in the area-weighted average year of the inventory (1978) and the modelled result (1980) would be negligible.

The distribution of biomass C across inventory units (spatially aggregated by polygons, typically 10 km × 10 km) in this region was examined (Fig. 4a). Almost 35% of the cells have an average biomass C in the range of 40–50 Mg C ha^{-1}. The distribution of biomass C is very close to a normal distribution about the average.

Table 1
Comparison of biomass carbon estimated from the 1994 Canadian forest inventory (8.54 Mha, average sample date 1978) and from the CBM-CFS2 (9.36 Mha, Calibrated with Bonnor, 1985 biomass inventory using the 1981 Canadian volume inventory)

	Total biomass C (Tg)					Biomass C density (Mg ha^{-1})				
	CanFI94				Total CBM-CFS2	CanFI94				Total CBM-CFS2
	Softwood	Hardwood	Mixedwood	Total		Softwood	Hardwood	Mixedwood	Total	
Total	275	73	78	426	404	49	42	62	50	43
Hardwood component	21	55	29	105	81	4	32	23	12	9
Softwood component	254	18	50	321	323	46	10	40	38	35

Inventory and model biomass C estimates were also compared aspatially, based on the percentage of area in different biomass C categories (Fig. 4b). These data show that the inventory and model distributions follow a similar trend, however, the percentage of area in the 0–10 and 10–20 Mg C ha^{-1} biomass C classes is greater for the model estimate than for the inventory estimate. Conversely, for the biomass C classes from 20 to 50 Mg C ha^{-1}, estimates from the inventory are greater than those from the model. This is, in part, because older age classes do not necessarily contain a high biomass C (due to lower productivity (Fig. 2), growth curve 18) and younger age classes do not necessarily contain a low biomass C (due to higher productivity (Fig. 2), growth curve 2). Consequently, the age class structure of the area is not necessarily associated with an unique biomass class distribution. Since the model was calibrated on the basis of age class distribution (Kurz et al., 1992), differences between the modelled and inventory biomass class distribution can be expected. As a result of proportioning more area to smaller biomass classes (Fig. 4b), it is reasonable to expect a lower total biomass C estimate from the model (Table 1).

The variation in growing conditions across the area, as well as different site disturbance histories (timing and type), are not likely to be well represented by an average value. As a result, extraction of a biomass C estimate at any particular point on the landscape may not coincide with either the average from CBM-CFS2 or the inventory. The present distribution of C density across the region is influenced by the spatial distribution of disturbance events and changes in this distribution over time. If disturbance

Fig. 3. Area represented by the date of inventory from the 1994 Canadian Inventory

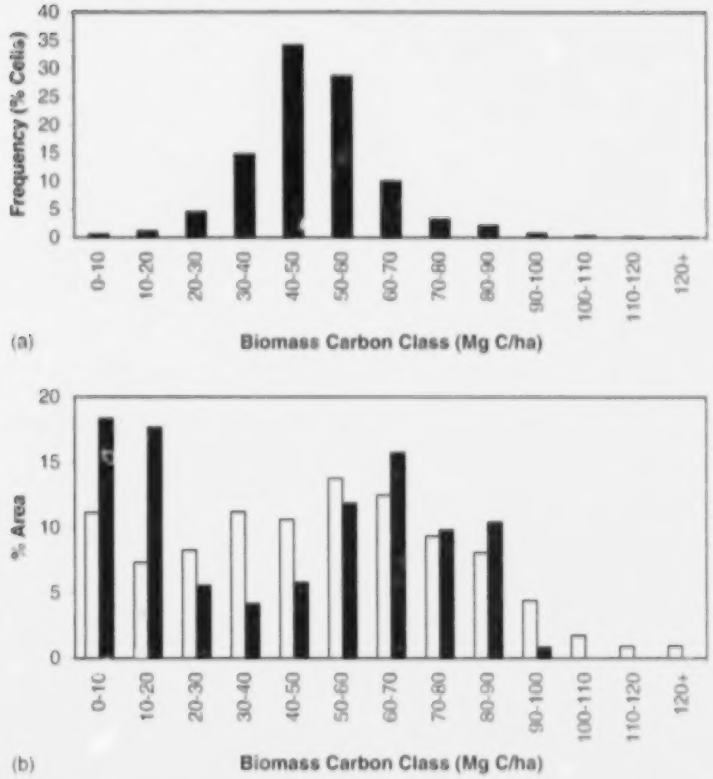

Fig. 4. Biomass carbon distribution: (a) the distribution based on the average biomass C per CanFI94 spatial unit; (b) the CBM-CFS2 (shaded bars) and 1994 inventory (clear bars) aspatial biomass C distribution.

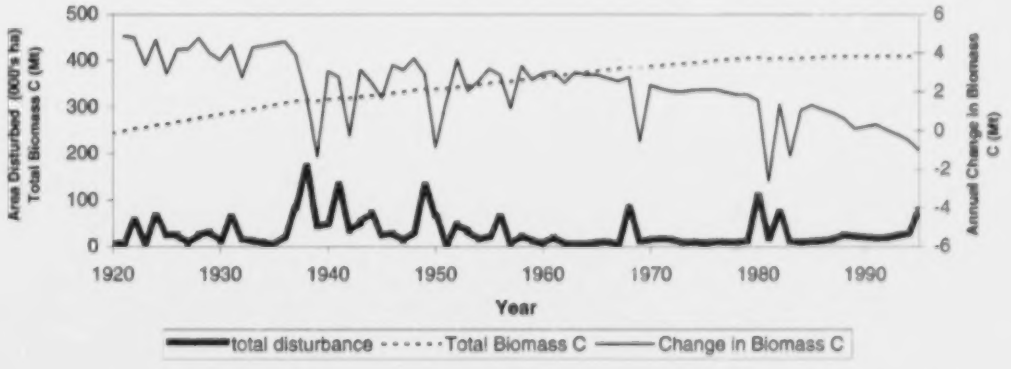

Fig. 5. Area annually disturbed by stand replacing disturbances based on historical record, CBM-CFS2 estimated change in aboveground biomass (excluding submerchantable stems), and the annual change in biomass C from 1920 to 1995 for the region. (Adapted from Kurz and Apps, 1999, using unpublished data.)

events and growing conditions changed such that a non-normal distribution (e.g. skewed, or binomial) occurred, the estimated average biomass C density would be representative of a much smaller portion of the area, depending on the extent of the skew and spread of the distribution.

3.2. Factors influencing biomass variability

Several factors influence the variability of biomass C across the landscape including climatic conditions, disturbance history, successional stage, vegetation distribution, and site factors. At the regional scale,

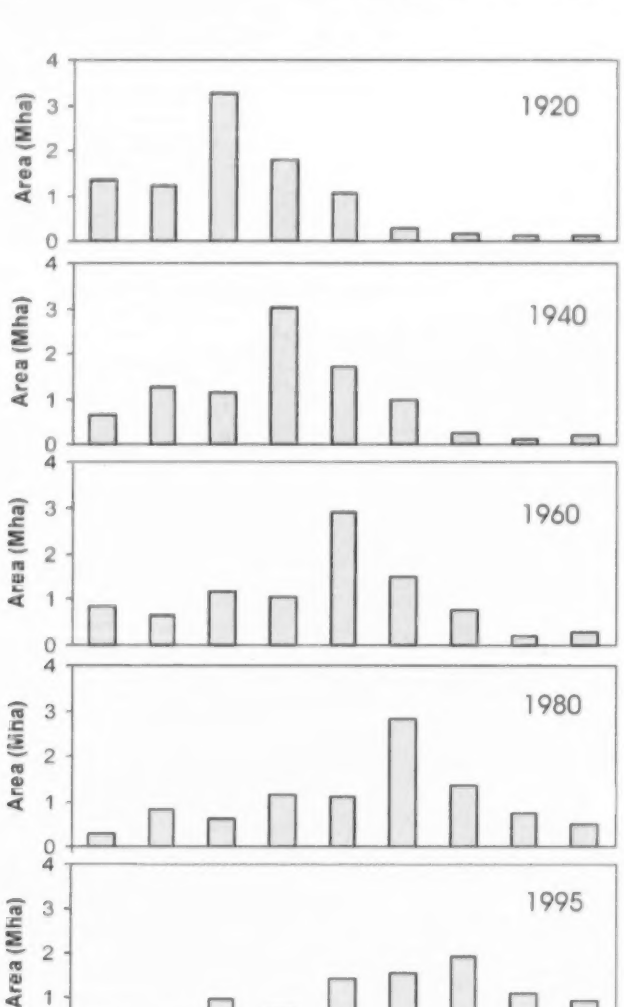

Fig. 6. Model simulated temporal change in the age–class structure of the study area from 1920 to 1995.

disturbances determine the age class distribution of the forest (Kurz and Apps, 1993). Since biomass C varies by stand age, changes in the overall age class distribution will affect the total biomass C pool. The area annually affected by stand replacing disturbances (harvest, fire and insects) for the study area from 1920 to 1995 as well as the change in the biomass C (Kurz and Apps, unpublished data from Kurz and Apps, 1999) is shown in Fig. 5. Historically in this region fire has disturbed a significantly greater area than harvesting and insects combined. The effect of the area disturbed is reflected in the annual change in biomass C. Although the change is dominantly positive, sharp reductions in the annual accrual of biomass C for the region occur, corresponding with years of increased area disturbed. The effect of disturbance on biomass C is also reflected in changes to the age class distribution (Fig. 6). There is an overall decrease in disturbance during the simulation period (Fig. 5), the age class distribution shifts to the right, with more forest area being transferred to the older age classes, resulting in a corresponding overall increase in biomass C. However, the rate of accumulation is decreasing throughout the period, a consequence of the trend towards an older age class distribution, since older stands accumulate biomass at a slower rate than younger more vigorous stands (Turner and Long, 1975; Attiwell, 1979; Long and Smith, 1992).

3.3. *Influence of local site factors on productivity*

The relationships between N and biomass C and clay content and biomass C were developed using plot data on upland sites from LaRoi and Pluth (1986). The significance of the relationships between soil clay content and aboveground biomass ($r^2 = 0.68$) shown in Fig. 7a suggests that soil clay content plays a major role both in providing soil nutrients and the physical environment for plant growth (Bhatti and Apps, 2000). The results are consistent with those of Bhatti and Apps (2000) for the same range of clay content in the boreal zone. The range of % clay used to develop the relationship (between 5 and 40%) captures most of the variation in clay content over the region (Fig. 8a) and consequently can be used to provide tentative estimates or modify estimates of biomass C on specific sites in the region.

Litter, fermentation and humus layer (LFH) nitrogen was also found to be related to biomass C (Fig. 7b)

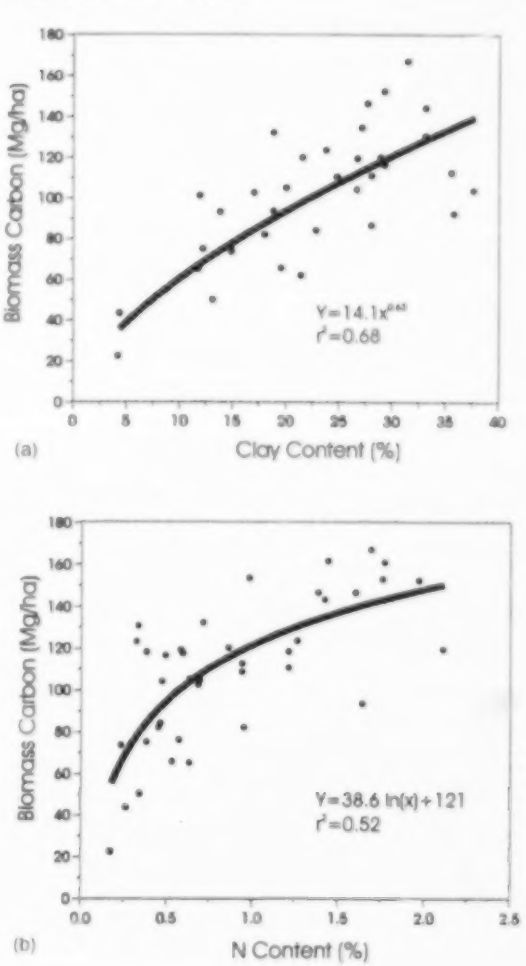

Fig. 7. Local scale relationships developed using 40 sites (from LaRoi and Pluth, 1986): (a) clay content of total soil column relation to aboveground tree biomass; (b) LFH nitrogen content in relation to aboveground tree biomass.

and has a distribution over the area ranging from 0.2 to 2.2% N. Although both clay content and total N are correlated to aboveground biomass, total soil N is also strongly related to clay content (Bhatti and Apps, 2000). Therefore, clay content can be used as a predictor/modifier of biomass accumulation on upland sites in this region. In this way, soil texture can provide site-specific adjustments to biomass C accumulation predictions in different stands.

The biomass-to-clay relationship (Fig. 7a) was applied to estimate the variability in mature biomass

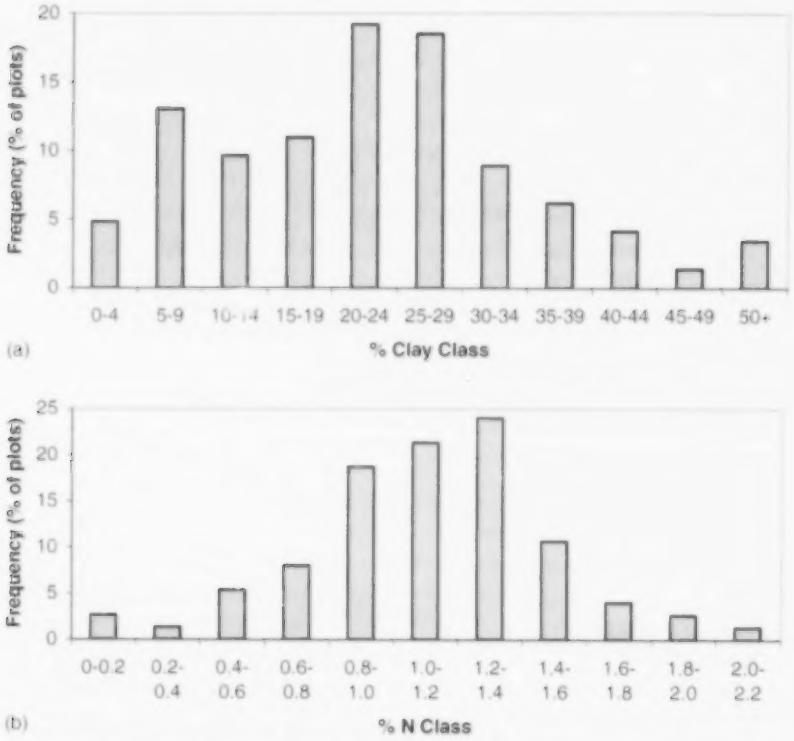

Fig. 8. Variation in site factors across the study area based upon sites from the (non-random sample) Siltanen et al. (1997) dataset: (a) distribution of % clay; (b) distribution of % N in the LFH layer.

C across the region. The predicted biomass for the plots had a mean biomass C of 98 t/ha, a minimum of 21 t/ha, maximum of 199 t/ha (standard error of the mean of 2.89). Derived for mature stands on highly productive sites, this biomass estimate represents the potential biomass, and not necessarily that actually achieved at each plot. Using this and similar relationships the biomass achieved at maturity can be predicted for sites that are not necessarily currently in a mature state. For modelling, this helps alleviate the problem with using chronosequence data to derive a growth curve for a region, enabling the inventory predicted growth curve to be modified using site variables.

3.4. Forest floor and total soil carbon

The estimates of forest floor C were very similar for all methods: CBM-CFS2, CSOCD and plot data (Table 2). For total soil C estimates, the CSOCD estimate (8.3 kg m^{-2}) was somewhat lower than the plot sample (14.8 kg m^{-2}) and the CBM-CFS2 estimate (15.6 kg m^{-2}).

There are differences between estimates due to the variability in actual soil C across the landscape and the sampling intensity and type of data collection used to derive an estimate. Data from Siltanen et al. (1997) are point estimates compiled from other datasets and are

Table 2
Soil carbon estimates from CBM-CFS2, the CSOCD, and from plots (Siltanen et al., 1997)

Source	Forest floor C (kg m^{-2})	Total soil C (kg m^{-2})
CBM-CFS2	3.3	15.6
CSOCD	3.4	8.3
Plots	2.9	14.8

not randomly selected. However, the CSOCD is an area based polygon estimate, in which the classification of forest land does not necessarily match the sites assembled by Siltanen et al. (1997). The definition of what is considered 'forest land' is a confounding issue. Definitions of forest land as opposed to wetland and peatland are not strictly defined and consequently, estimates derived from one data source examining productive forest land can overlap with another classification if based on soil properties (e.g. depth of organic matter) as is the case with the CSOCD (Bhatti et al., 2002).

The CBM-CFS2 soil C pool is initialized using an average value of 13.8 kg m^{-2} taken from the data of Zinke et al. (1986) and consequently reflects any bias in that estimate. When initialized using two different datasets (Zinke et al., 1986; Siltanen et al., 1997) for the entire Cordilleran ecoclimatic province in Canada, the CBM-CFS2 simulated a 37% difference in the resultant DOM pool but no significant difference in the overall ecosystem dynamics and net fluxes (Kurz and Apps, 1999). Heath and Smith (2000) drew similar conclusions regarding the relative importance of factors affecting uncertainties in C pools compared with those affecting fluxes.

4. Summary

The CBM-CFS2 estimates of biomass C are in agreement with the inventory biomass data. Biomass C across the region, grouped by CanFI94 polygons, was normally distributed both around the simulated and inventory average biomass estimates. This agreement is found even though the CBM-CFS2 was calibrated using a biomass inventory (Bonnor, 1985) which used a factor approach to estimate biomass (Bonnor and Babyn, 1984) for some provinces (including Alberta), and was based on an earlier volume inventory (1981), while the inventory biomass estimate was calculated using a different approach (Penner et al., 1997) and was derived from a later volume inventory (1994).

Although reasonably close for larger biomass C classes, the CBM-CFS2 estimates more area with lower biomass than the inventory estimate. This difference arises, in part, because CBM-CFS2 was calibrated on the basis of age class distribution. This is not necessarily consistent with biomass class distribution since forest types have different biomass C densities for the same age class. There is also a degree of uncertainty inherent in the inventory estimate since inventory data collected before and after the average inventory year are assumed to occur at the average and consequently do not account for growth and depletion due to natural mortality and disturbances.

Forest floor C estimates from point data, polygon and modelled sources were in close agreement, and differences in soil C can be explained by differences in sampling protocol and the definitions of forest land as opposed to forested peatland or wetland employed. Modelled soil C pool estimates are strongly influenced by soil pool initialization, and thus strongly reflect the data source from which they were derived. An assessment of variability using soil pool estimates from different sources can be performed cautiously, as long as differences in the methodologies, and the effects on the soil C estimate are considered.

Within ecosystem types there is considerable spatial variability in site-productivity and the resultant biomass C pools. Disturbance frequency and amount changes the overall forest age class structure, affecting temporal changes in C dynamics. In this region, decreasing disturbances, likely associated with forest management and protection (Price et al., 1998), have led to an age class distribution with more area in older age classes, and an accumulation of biomass C. However, on a smaller scale, not only the frequency of disturbance, but the spatial distribution of these disturbances determines the variability of C stocks.

This variability is influenced by the site characteristics. Factors inherent in the spatial variability between sites such as available nutrients, moisture and local climate (induced by differences in topography) influence local scale C pools and fluxes. With a link between local variables and biomass dynamics, the prediction of C dynamics can be made to include the variation inherent across the landscape, and temporal variability under climate change can be explored.

The relationship between the site clay content and productivity were used to estimate the variation in biomass C in an area, as well as provide the means to model forest growth at a higher spatial resolution. A good relationship was found between site clay content and the biomass achieved at maturity. Using this relationship, the range in potential biomass for the

region was predicted (mean biomass C of 98 t/ha), and can be used to estimate the biomass achieved at maturity for sites not currently in the mature state. This is very useful for modelling growth on a local level when the only widely available information on the specific age–biomass dynamics is derived from a regional level. Inventory-based regional growth curves can thus be modified on the basis of site factors, accounting for some of the problems inherent in using chronosequence data to estimate stand growth. It is important to recognize the limitation of applicability of soil–site relationships (Carmean, 1975). Care must be taken to ensure that relationships like these are not used to make predictions to other areas where conditions may be such that the relationships change. These results and results from other studies in similar forest regions can be applied cautiously to a larger region. However, it is reasonable to use soil–site studies as long as they are generally representative of the larger area to which they will be applied, and are not relied on exclusively. The relationships examined here are with aboveground tree biomass at a mature state. As a result, soil texture and nutrient status can be used to estimate the potential biomass for a site, not necessarily what the site may be currently supporting.

Understanding the interacting processes, and the quantitative relationship between different C pools in forest ecosystems and site characteristics, climatic conditions, and disturbances on a finer scale are keys to improved projections of forest C budgets and their responses to climate change and management interventions. This preliminary work is a step towards giving us the ability to use inventory driven carbon budget models not only to predict C stock and flux over large areas, but also with higher precision, on a smaller scale. As site-specific relationships do not readily lend themselves to be extended beyond the range from which they were obtained, further work is required to determine which variable, or aggregate of variables are appropriate for different areas, and how they can be used to modify and predict stand growth dynamics.

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